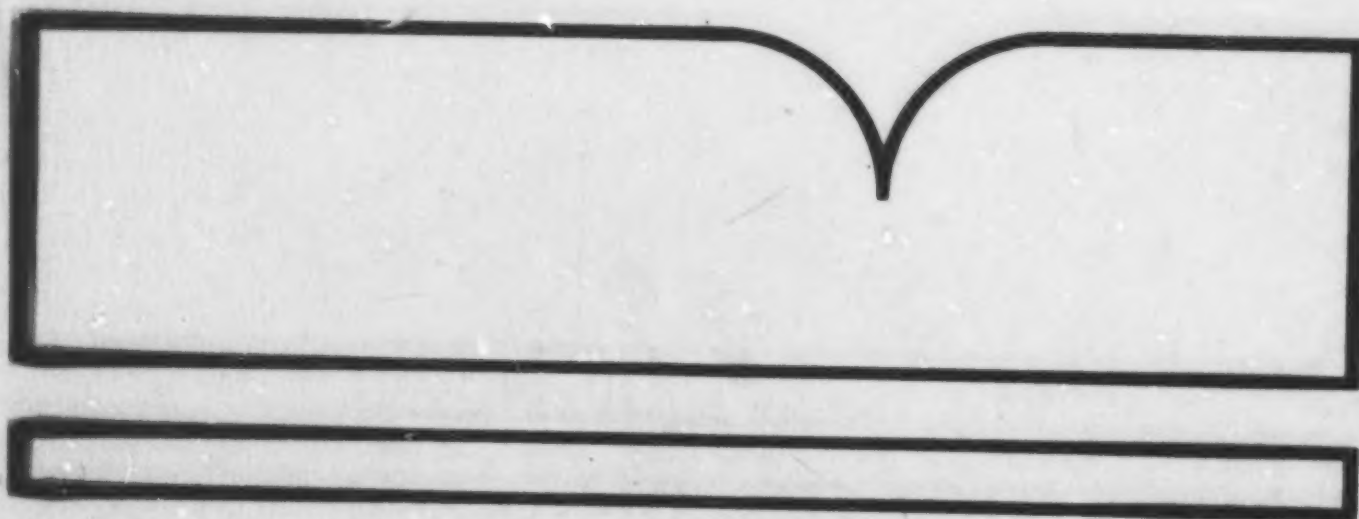


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Introduction to Artificial Ground-Water Recharge

(U.S.) Robert S. Kerr Environmental
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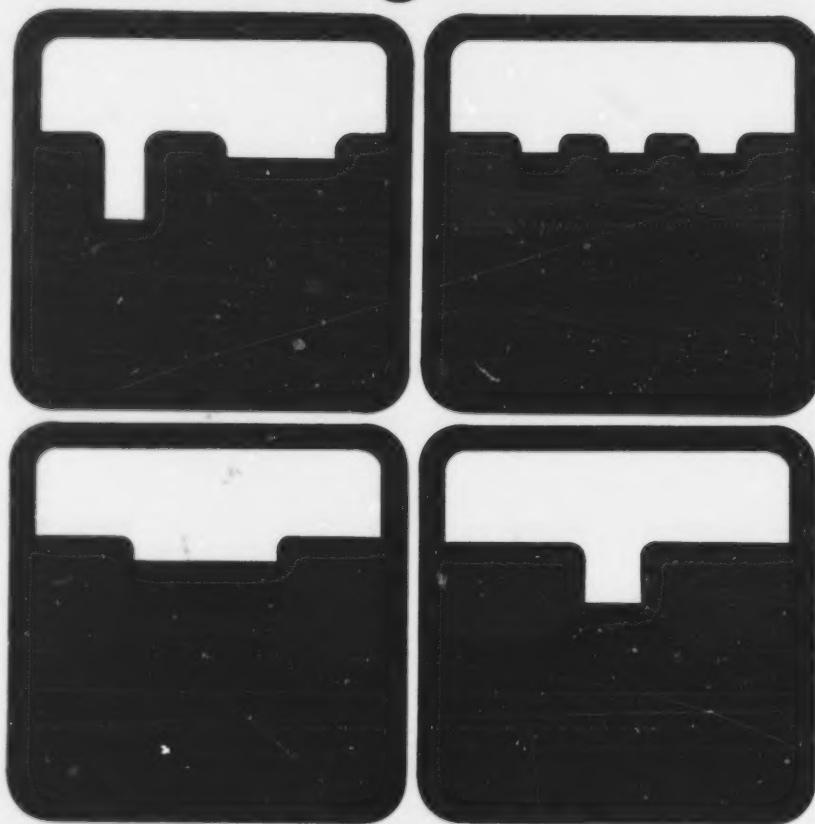
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Introduction to Artificial Ground Water Recharge



by Wayne A. Pettyjohn
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INTRODUCTION
TO
ARTIFICIAL GROUND-WATER RECHARGE

by

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ABSTRACT

Artificial ground-water recharge has been practiced for scores of years throughout the world. The purpose of artificial recharge is to increase the rate at which water infiltrates the land surface in order to supplement the quantity of ground water in storage. A variety of recharge techniques are feasible. Examples include methods that increase well yields, reduce the rate of decline of ground-water levels, reduce land subsidence, control seawater intrusion in coastal areas, and renovate wastewaters.

Two broad types of artificial recharge are water spreading and well systems. In the former, large areas of land may be flooded, basins constructed, ditches or furrows excavated, or existing stream channels modified. Water is diverted to these structures where it infiltrates. Recharge wells consist of shallow, relatively large pits or shafts or screened wells. Waters used for recharge commonly include stream flow, municipal wastewaters, excess irrigation water, and cooling water.

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SECTION 1

GROUND WATER AND ARTIFICIAL RECHARGE

GROUND WATER

Water from wells, seeps, and springs is derived from underground sources and is called ground water. Vast quantities of ground water are held in transient storage in the saturated part of the earth's crust. The stored ground water slowly migrates to streams, springs, and wells, and when it reaches and flows from these points of discharge the quantity in the ground is reduced. On the other hand, the amount of ground water in storage fluctuates annually. Generally, in the spring the water table is high and there is more water in storage than there is during late summer and fall after the water table has declined.

Ground water is derived primarily from rain and snowmelt that infiltrates the land surface and slowly percolates to the water table. This process of adding water to underground storage is called natural ground-water recharge or, simply, recharge. Where the materials forming the earth's surface are coarse and the slope of the land is gentle, there is generally more ground-water recharge than there is in areas where the strata consist of fine-grain materials, such as shale and clay, or where the slope is steep.

Ground water in storage may be depleted at an alarming rate during droughts due to the increased pumpage of water from wells and the decrease in natural recharge as a result of reduced precipitation. Normally, however, the water level recovers once the drought is over. Substantial water-level declines also occur where, over a long period of perhaps several years, pumping exceeds the natural rate of recharge.

Hydrographs (graphs of water-level fluctuation versus time) illustrating the fluctuation of the ground-water level during a period of several years in two wells in Texas are shown in Figure 1. The hydrograph of a well in San Antonio, which taps the Edwards and associated limestones, illustrates not only the annual water-level fluctuation but also the effects brought about by periods of reduced rainfall and recharge (1956, 1963-64, 1967-1971). Nonetheless, the long term water level has remained rather constant, indicating a net balance between recharge and discharge. Conversely, the water level in a well tapping the Lissie-Willis sand in the Houston area is characterized by a continual long term decline upon which is superimposed annual cycles. In this case the water level declined more than 43 m (140 ft) during a 20-year period, reflecting a considerable difference between recharge and discharge because of pumping.

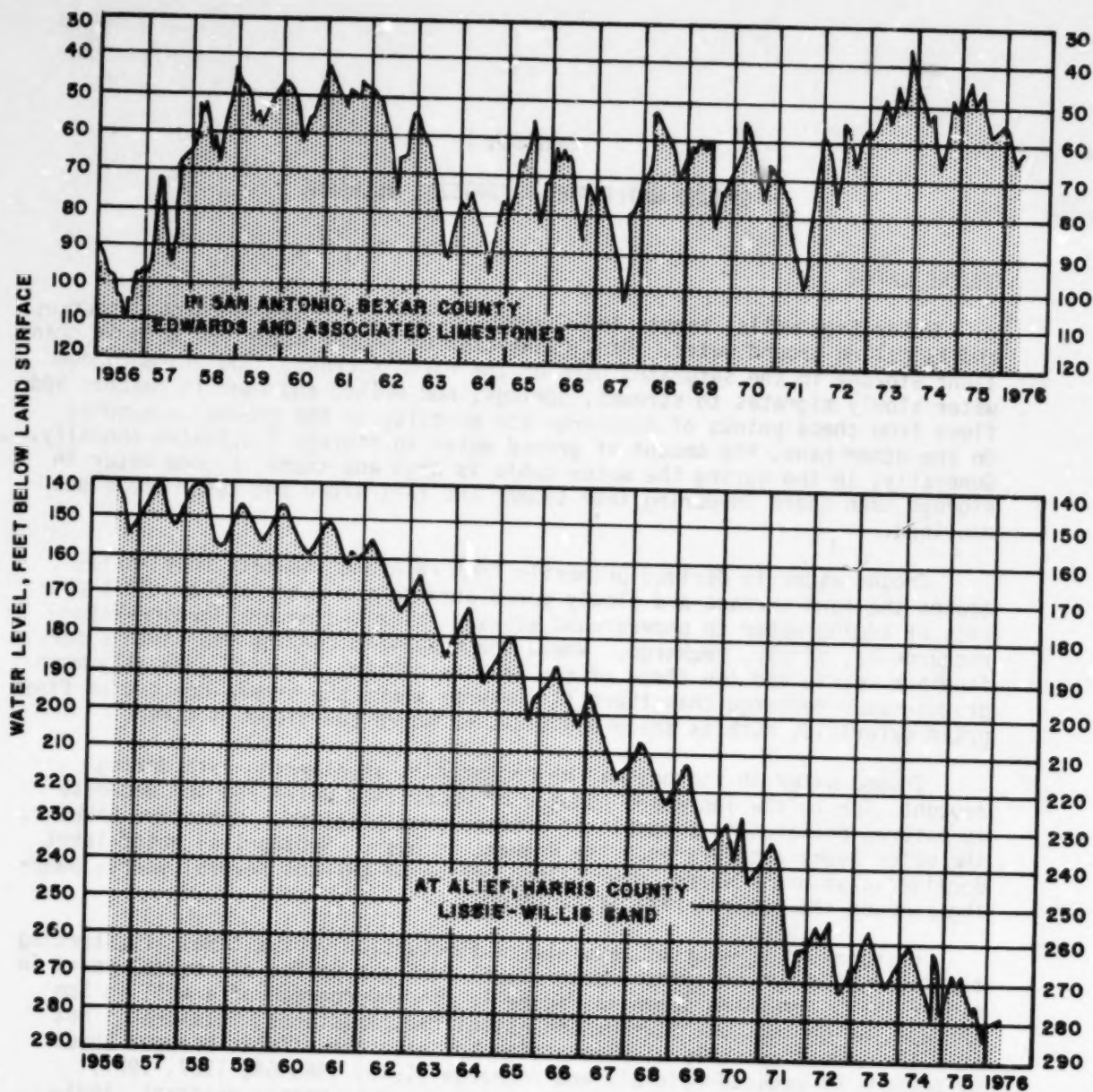


Figure 1. Hydrographs of two wells in Texas. In the upper case, the long-term trend is rather constant in spite of a few short-lived declines. In the lower case, pumping exceeds natural replenishment and there is a long-term decline.

Long term water-level declines, which indicate diminishing amounts of water in storage, may lead to several vexing problems, including reduced well yields and, perhaps, land subsidence, the intrusion of salty water in coastal areas, or inland the leakage into the aquifer of highly mineralized water. The most common problem is decreased well yield, which may lead to water shortage and rationing.

Land subsidence occurs when water is squeezed out of layers of clay, permitting them to be compressed. The reduction in rock volume is expressed by sinking of the land surface. In the southern part of the Great Valley of California and in Mexico City, for example, maximum subsidence has probably exceeded 5 m (15 ft) and definitely exceeded 3.3 m (10 ft) over relatively large areas. Intrusion of sea water occurs because the removal by pumping of fresh water allows salty ground water to migrate inland, perhaps to contaminate water supplies. Sea water intrusion is not uncommon along parts of the Atlantic, Gulf, and Pacific Coastal regions of the United States.

ARTIFICIAL RECHARGE

Artificial recharge is a means of augmenting the natural infiltration of surface water into a ground-water reservoir at a rate that vastly exceeds that which would occur naturally. It includes a variety of methods, such as wells or other specialized construction, water spreading, or changing natural conditions. Other than induced infiltration, the two major techniques of artificial recharge are surface spreading and injection wells. In surface spreading methods, large areas of land may be flooded, basins constructed, ditches or furrows excavated, or existing stream channels might be modified. Water is diverted into these catchment structures and allowed to infiltrate. Recharge or injection wells might consist of shallow, relatively large pits or shafts, or screened wells. Recharge wells and shafts permit direct access from the surface water source to the ground-water reservoir.

Artificial ground-water recharge techniques have been used throughout the world for more than 200 years for a variety of purposes. These include but are not limited to the following:

1. Ground-water (well field) management
2. Reduction of land subsidence
3. Renovation of wastewater
4. Improvement of ground-water quality
5. Storage of stream waters during periods of high or excessive flow
6. Reduction of flood flows
7. Increase well yield
8. Decrease the size of areas needed for water-supply systems

9. Reduction of salt-water intrusion or leakage of mineralized water
10. Increase stream flow
11. Store fresh water, derived from rain and snowmelt. If the existing ground water is saline, the less dense lens will float on the saline water.
12. Secondary recovery of oil

In addition to designs and structures contrived solely for artificial recharge, a large quantity of water and wastewater provides uncontrolled, unmonitored and nondeliberate recharge. Inadvertant ground-water recharge includes, among others, the fluids that infiltrate from waste disposal, treatment or storage facilities, particularly those methods utilizing excavations, mines, and ponds. It also includes the waters applied for irrigation, some of which infiltrates to the water table carrying increased concentrations of a variety of dissolved salts and agricultural chemicals. Both above and underground facilities can also lead to inadvertant ground-water recharge. Examples include leakage from pipelines and sewers. Along the same line are included accidental spills, which might occur by the wrecks of trains or transport trucks, as well as leakage of fluids from storage tanks. Other sources of nondeliberate recharge include dry wells, drainage wells and canals, well disposal of wastes, septic tanks, cesspools, and privies, as well as mines.

Induced infiltration is an indirect method of ground-water recharge. When a well that lies close to a lake or stream is pumped, the water level in the vicinity of the well declines to form a cone of depression. If the ground-water level declines to such an extent that it is lower than the water surface of the lake or stream, water will begin to flow into the ground and then toward the well. The well induces recharge by changing natural conditions. In many cases, infiltration galleries and collector wells are the major means of extraction rather than typical vertical wells. Induced infiltration supplies commonly produce large amounts of water over long periods and may provide a more reliable source than wells that depend solely on natural recharge. On the other hand, induced water supplies closely reflect the chemical quality of surface water and if the latter becomes polluted, the induced water may degrade the aquifer.

The water commonly used for artificial recharge includes natural stream flow, high flows diverted from a nearby water course, or cooling waters. In some places, storm drainage water has been collected and then allowed to infiltrate through basins or wells. In many parts of the world, sewage effluent, either treated or untreated, has served as a major source of recharge water. This source is becoming more attractive, both technically and economically, because water that would normally flow to waste can be effectively treated by means of land disposal systems from whence it infiltrates, eventually to become ground water.

Land application of wastes and wastewaters was practiced in Athens prior to the Christian Era and effluent irrigation was reportedly used in Germany

in the 16th century. The practice spread throughout Europe and continued in South Africa, Australia, and Mexico as those areas were colonized. Many of the successful farms employed underdrains to carry off the excess artificially recharged ground water to nearby streams.

The Department of Economic and Social Affairs of the United Nations (1975) described 31 sites, exclusive of the United States, where artificial recharge is either practiced or has been investigated. The examples reported are not comprehensive but rather point out the extensive use of artificial recharge throughout the world. By far, the widest use of artificial recharge in countries outside of the United States is to supplement dwindling municipal and industrial ground-water supplies or to improve their quality. Advanced techniques are utilized in Spain, Switzerland, Germany, France, Sweden, Israel, Egypt, Algeria, Iran, and the Latvian, Lithuanian, Turkmen, Uzbek, and Ukrainian Soviet Socialist Republics.

Artificial recharge is also extensively used to control salt-water intrusion in coastal areas of Australia, the Netherlands, Israel, Morocco, Senegal, Togo, Japan, and the United States. In Japan, artificial recharge is also being practiced to reduce land subsidence in areas of excessive pumping and in Romania, Bulgaria, and France it is used to supplement irrigation water obtained from ground-water sources.

Artificial recharge has been practiced in the United States for nearly a century and probably at least one system is presently being operated in every State. The purposes of recharge vary widely, ranging from well-field management to waste disposal. The greatest number of systems are relatively small and are used to reduce the rate of water-level decline in order to avoid water rationing or to supplement the yield from existing well fields. Nearly all of the larger projects or systems are designed to either limit salt-water intrusion in coastal areas or to renovate sewage, or both.

Land treatment of sewage began in the United States in the late 19th century; these systems were developed exclusively for irrigation purposes. Seepage of water from irrigation canals (a type of artificial recharge) in Fresno County, California, was described as early as 1898. Even earlier (1890) recharge ponds were constructed along the South Platte River near Denver to increase the yield of infiltration galleries.

Induced infiltration supplies for both municipal and industrial needs are common along most of the major waterways and particularly adjacent to the Ohio and Mississippi Rivers and many of their major tributaries.

The largest regional effort of artificial recharge is being carried out in California where as early as 1895 flood waters were spread over the alluvial fan at the mouth of the San Antonio Canyon to sustain the flow of wells in southern California's Upper Santa Ana Valley (Thomas and Phoenix, 1976). By the late 1950's, more than 50 different agencies were involved, in one way or another, with artificial recharge. Most of the projects were in the San Francisco Bay, Tulare, and southern coastal regions. About 65% of all the projects utilized recharge basins or pits and these accounted for about 60% of the water recharged. Natural channels, ditches, and furrows accounted for

almost 40% of the water artificially recharged, while wells provided only about 1%. Water used for these systems was obtained locally, from the Central Valley, or from the Colorado River.

Nearly 40% of the water used in Los Angeles each year is derived from aquifers that have been artificially recharged with storm runoff and other surplus water. The value of the water approaches \$50 million a year (Saines, 1974). The water is recharged through 36 spreading basins that total a combined area of 13 square kilometers (five square miles).

The arid to semiarid climate of much of California, coupled with large urban population centers, industry, and an enormous agricultural output based on irrigation, has had a significant impact on the region. The extensive use of ground water and the diversion of stream flow to reservoirs and irrigation tracts caused significant water-level declines and reduction of stream flow. This, in turn, led to land subsidence, largely in the Central Valley, seawater intrusion into fresh water coastal aquifers, and induced salt water recharge from tidal rivers, particularly in the San Francisco Bay, Central and South Coastal Regions, and depletion of water in storage in many other places. These adverse effects of surface and ground-water use necessitated much of the research, experimentation and utilization of artificial recharge techniques in the United States.

SECTION 2

ARTIFICIAL RECHARGE--CONSIDERATIONS AND METHODS

CONSIDERATIONS

The type of artificial recharge system that can be developed at any specific site is controlled, to a large degree, by the geologic and hydrologic conditions that exist at that site. Site selection criteria, in addition to economic considerations, should include at least the following:

1. Source of recharge water
2. Chemical and physical characteristics of the recharge water
3. Availability of an aquifer suitable for artificial recharge
4. Thickness and permeability of the material overlying the aquifer, if any
5. Thickness and permeability of the aquifer
6. Chemical characteristics of water in the aquifer
7. Proximity of the potential recharge site to an appropriate well field cone of depression
8. Water-level differences between the aquifer and the recharge site
9. Topography
10. Availability of property

Availability of water, either on a perennial or intermittent basis, is of prime concern in any recharge operation. In some cases, impoundment structures may be necessary for temporary surface storage and to increase natural recharge.

The chemical and physical characteristics of the recharge water are important for several reasons. First, the chemical quality of the surface water must be compatible with that in the aquifer in order to avoid chemical reactions that might reduce the permeability of the aquifer. Secondly, it is essential that the recharge water does not contain toxic chemicals, such as those derived from some industrial wastes or pesticides, since this could contaminate the ground-water supply. Finally, it is advantageous to use water

that is low in sediment (turbidity) because fine-grained materials may rapidly plug a recharge system and perhaps reduce the permeability of the aquifer as well.

The aquifer to be recharged must underlie the potential recharge site. In areas of complex subsurface conditions, particularly where there is interfingering of coarse and fine-grained rock units, it is not always a simple task to determine aquifer interconnections. Furthermore, the aquifer must have sufficient permeability and thickness to rapidly carry away the recharged water. An aquifer that is tapped by high yield wells should be suitable for artificial recharge. Additionally, the recharge site must lie within the influence of a well field cone of depression so that the recharged water has an opportunity of flow down gradient in the direction of pumping rather than elsewhere.

The thickness and permeability of the earth materials overlying the de-watered aquifer exert a strong influence on the type of recharge system that can be constructed. When these materials are thick and of low permeability, recharge wells are in order, but where thin or more permeable, spreading basins, large shafts, or irrigation may be satisfactory.

The water level in the aquifer must be lower than the operational water level in the recharge system so that the water will infiltrate. The difference in water level, or the depth of water in a basin, is the driving force that allows the water to infiltrate.

Topographic relief of a potential artificial recharge facility may limit design capability. Water spreading, irrigation, and land treatment systems require land that is relatively flat, while the topography may have little or no influence on an injection well system.

In urban areas land acquisition for recharge facilities may provide a significant hurdle since the most favorable locations may be preempted. Industrial areas should be avoided, if possible, because of the possibility of contamination.

ARTIFICIAL RECHARGE TECHNIQUES

Induced Infiltration

Induced infiltration supplies depend, to a large extent, on the quantity of water that can be diverted from a stream or lake. Pumping a streamside well establishes a hydraulic gradient from the surface source to the well (fig. 2). Both vertical and horizontal wells are used for this purpose. The controlling factor, other than a dependable source of surface water of acceptable quality, is the permeability of the streamside deposits and the sediment on the bottom of the stream. In areas where the stream is separated from the aquifer by materials of low permeability, leakage from the stream may be so small that the system is not feasible.

The permeability of a stream bottom fluctuates throughout the year. During periods of low flow, mud and organic matter accumulate in the channel forming a bed of low permeability that reduces infiltration. The channel is scoured during high flows. The rate of infiltration can vary by 50% or more between

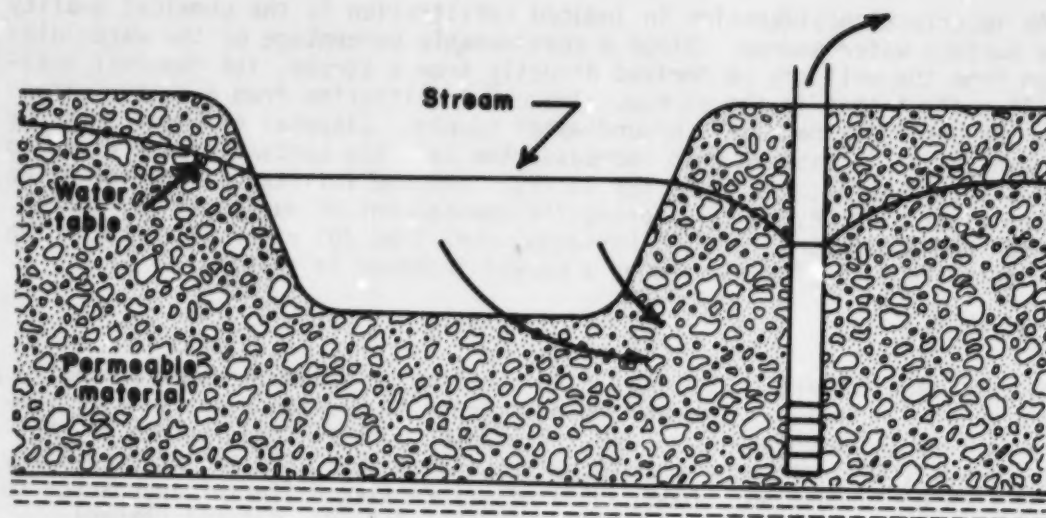


Figure 2. An induced infiltration supply draws water from a stream into the ground.

periods of high and low flows. In many places, and particularly during droughts or extended dry periods, stream discharge is not sufficient to erode the fine materials from the channel bottom. This situation may be rectified by dredging.

Where saturated streamside deposits are thin, horizontal wells may be more feasible and appropriate than vertical wells. Laterals which radiate from a central collector well can be injected so that they lie close to the bottom of the aquifer and allow the maximum amount of drawdown (fig. 3).

An important consideration in induced infiltration is the chemical quality of the surface water source. Since a considerable percentage of the water discharged from the well may be derived directly from a stream, its chemical quality will reflect that in the stream. Induced infiltration from a contaminated stream may seriously degrade a ground-water supply. Disposal of brine into the Tuscarawas River in eastern Ohio increased the chloride content of the river to more than 6,000 mg/l (milligrams per liter). Induced infiltration of the brine-enriched river water eventually forced the abandonment of municipal wells at Barberton and Coshocton. Even at Marietta, more than 200 river miles below the waste source, municipal wells showed a marked increase in chloride.

Water Spreading

As the term implies, water spreading consists of allowing water to mantle a large area at a relatively shallow depth in order to provide a substantial surface area through which the water can infiltrate. Controlling factors on the amount of artificial recharge are (1) water contact time, (2) soil permeability, and (3) area of inundation. Todd (1959) described five different approaches to water spreading. These include flooding, basins, ditches, natural channel method, and irrigation.

Flooding--

Nearly level or only gently sloping land is required for flooding methods of artificial recharge. Water is diverted by canals or other structures from the water source to the recharge site. Surface velocities are kept to a minimum in order to reduce erosion as the water flows across the recharge site to a point of collection. Excess water that runs off the plot may be collected in a down-gradient ditch or canal and either returned to the source stream or used for some other purpose.

Basins--

Artificial recharge basins commonly are formed by either excavation or by building low head dams across natural waterways (fig. 4). They commonly lie in ephemeral or intermittent stream channels or parallel to them.

An advantage of the basin method is that whatever space is available can be used. Furthermore, they are easy to construct and maintain. The rate of recharge from individual basins is directly related to the permeability of the materials between the bottom of the basin and the water table.

Ditches--

In some areas it is feasible to excavate a series of ditches, trending slightly down the topographic slope, that originate at a major feeder canal

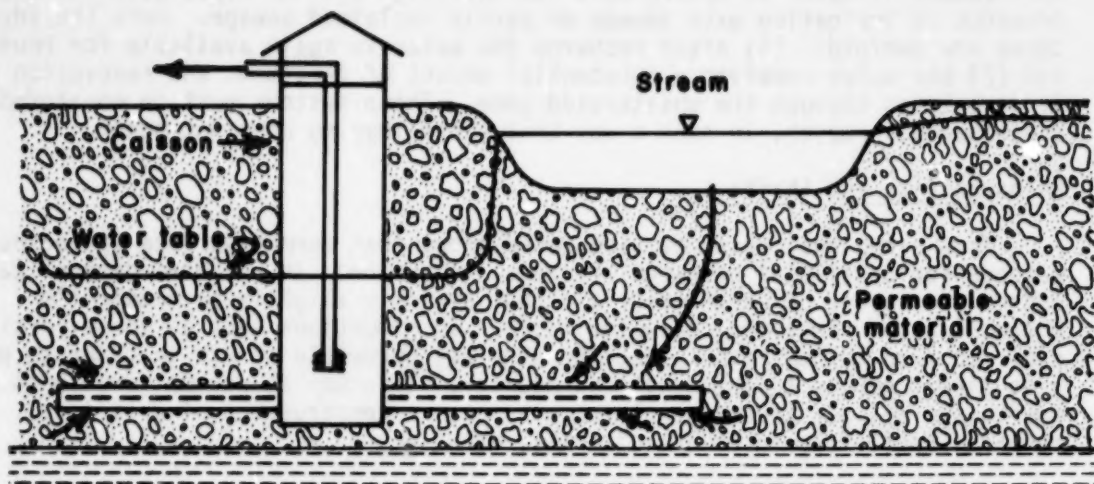


Figure 3. Some induced infiltration supply systems consist of large diameter caissons from which extend horizontal slotted pipes (laterals). These systems commonly provide yields of several thousands of gallons per minute.

(fig. 5). This type of system may resemble a herringbone pattern. The ditches should terminate in a collection canal designed to carry away the water that does not infiltrate in order to avoid ponding and reduce the accumulation of fine material. A ditch system can be designed to best suit the topographic and geologic conditions that exist at a potential artificial recharge site.

Natural Channel Modifications--

In order to increase both the time and area of water coverage in a channel, a number of structures can be built. Other than channel dredging, straightening and widening, low head check dams are the most popular method for increasing recharge from existing streams or ephemeral channels.

Irrigation--

Irrigation, particularly during the nongrowing season, may add a significant amount of water to underground storage (fig. 6). An especially attractive prospect is irrigation with sewage or partly reclaimed sewage. Here the advantages are twofold: (1) after recharge the water is again available for reuse and (2) the water receives a substantial amount of treatment and renovation as it percolates through the unsaturated zone. These systems must be monitored and managed, however, in such a way that water logging does not occur.

Recharge Pits and Shafts

From a regional point of view, conditions that permit surface spreading methods for artificial recharge are relatively rare. In the more general case, lenses and layers of earth materials that are only slightly permeable lie between land surface and the water table. In situations such as these, artificial recharge systems must penetrate the less permeable strata in order to provide direct access to the dewatered aquifer. This may be accomplished with pits, shafts, or wells. These structures also permit construction of artificial recharge facilities in relatively small areas.

Recharge pits are simply excavations, of variable dimensions, that are sufficiently deep to penetrate less permeable strata (fig. 7). Construction and maintenance are relatively simple and commonly inexpensive. In many places abandoned gravel pits have served as recharge pits (fig. 8).

Unfortunately, pits used for storage or treatment of liquid wastes provide a significant source of inadvertent recharge, which leads to complex and widespread problems of ground-water pollution. Examples include sewage treatment lagoons, industrial waste holding or disposal ponds and oil-field brine evaporation pits, to mention only a few of an exceedingly large number.

Recharge shafts are generally deeper and of smaller diameter than pits (fig. 9). Their purpose is also to penetrate low permeability layers. Shafts may be lined or unlined, open or filled with coarse material, and large or small. They are constructed by hand, with draglines and backhoes or are drilled or bored. Where the recharge water contains sediment, shafts may become plugged fairly rapidly.

Commonly, recharge shafts are used in conjunction with pits (fig. 10). Both suffer from decreasing recharge rates with time due to the accumulation

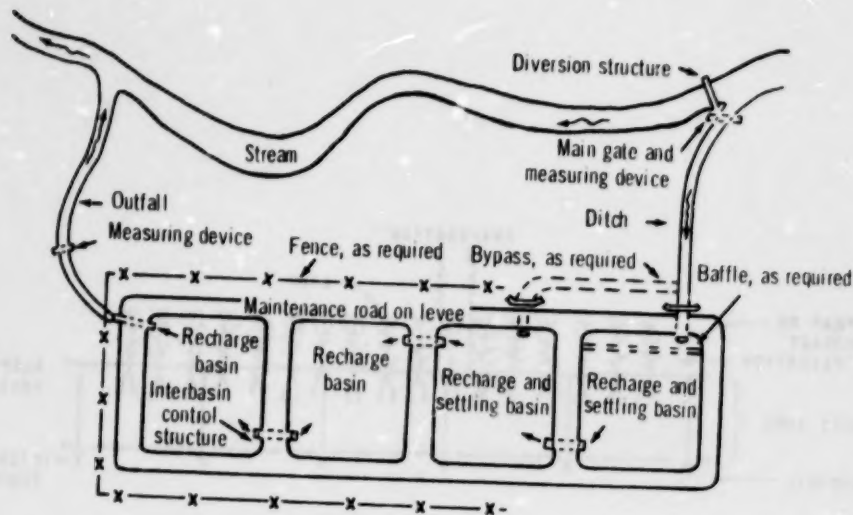


Figure 4. Typical plan of basin-type recharge project (Bianchi and Muckel, 1970, p. 46).

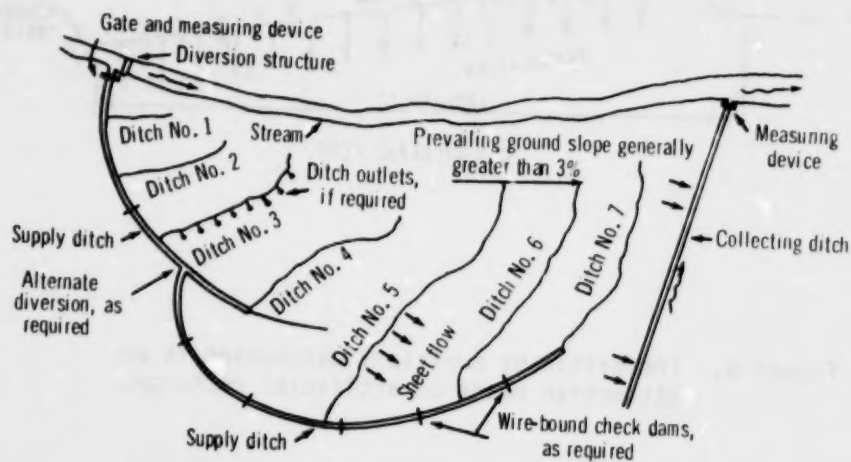


Figure 5. Typical plan of ditch-and-flooding recharge project (Bianchi and Muckel, 1970, p. 48).

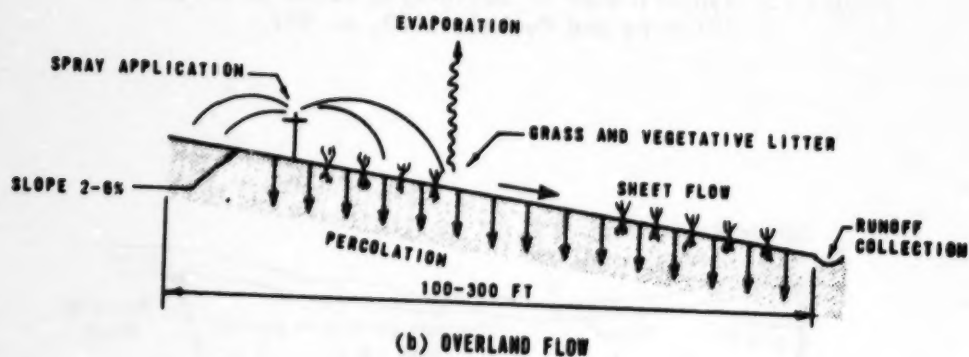
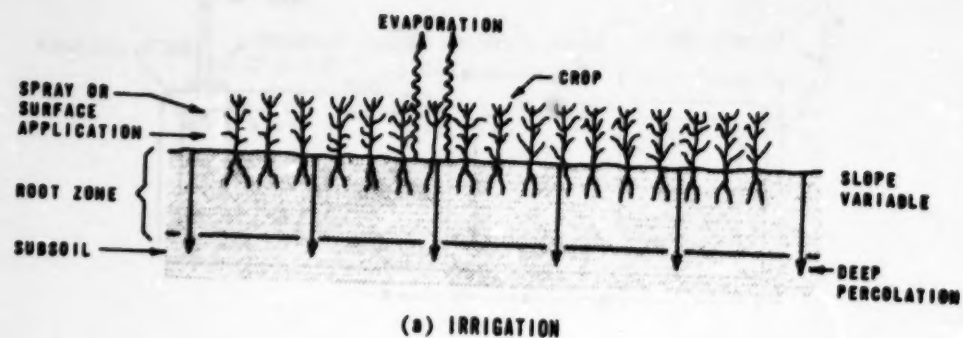


Figure 6. Irrigation by municipal wastewater is an attractive means of artificial recharge.

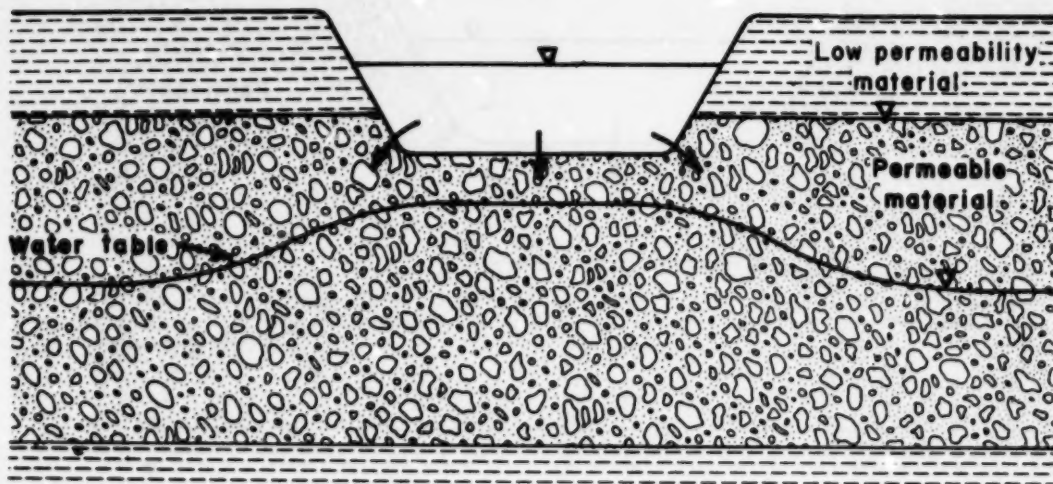


Figure 7. Recharge pits are excavated through fine-grained material and penetrate the upper part of an aquifer. They are effective and easy to construct and maintain.

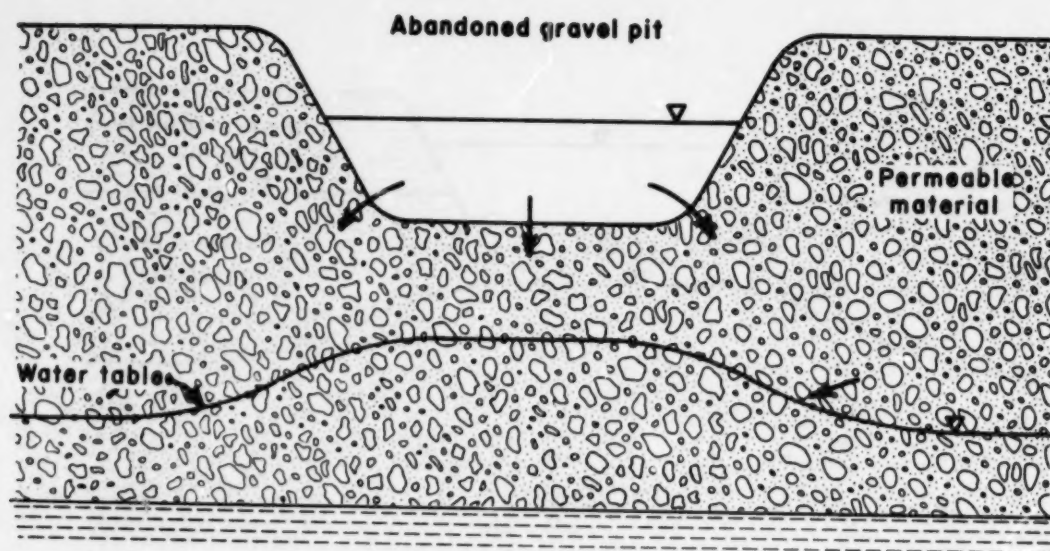


Figure 8. Abandoned gravel pits are commonly used for artificial recharge basins.

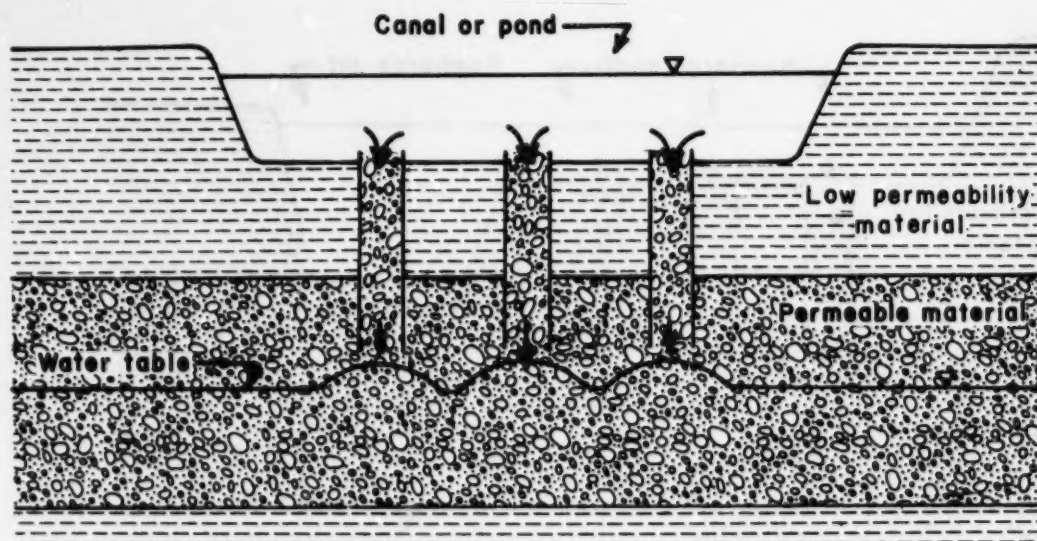


Figure 9. Recharge shafts are designed to provide a conduit through materials of low permeability and permit direct access to the aquifer.

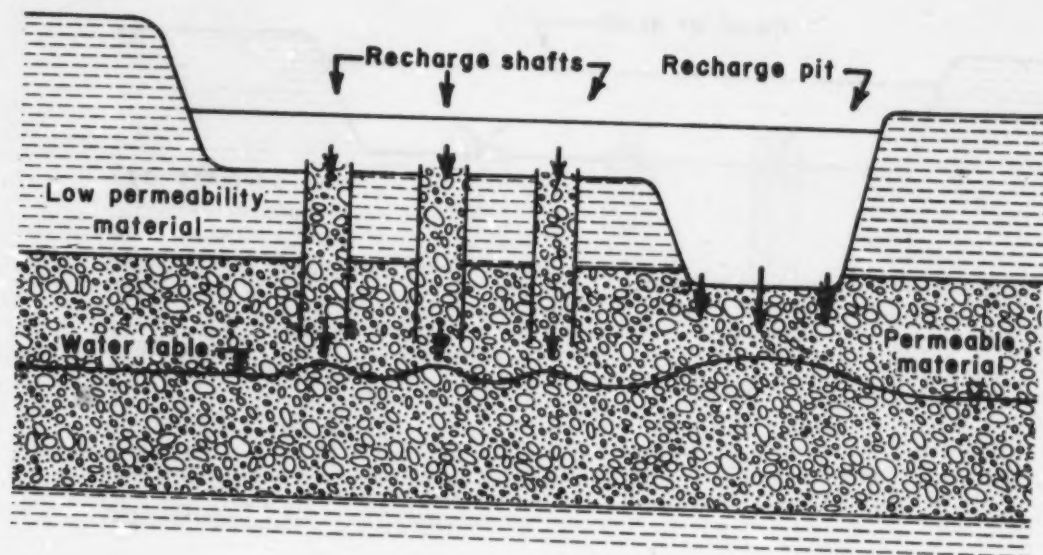


Figure 10. Where land is not readily available for recharge facilities, a combination of recharge shafts and pits permits achievement of maximum rates.

of fine-grained materials and to the plugging effect brought about by microbial activity. Rates through recharge pits may be maintained by periodically allowing the facility to become dry or by scraping and removing the accumulated material from the sides and bottom. Shafts are less easy to maintain owing to their smaller diameter and greater depth. In some cases the coarse material used to fill the shaft must be replaced.

Recharge Wells

Recharge wells are used to tap deep aquifers. In many respects they are similar to water-supply wells except water is pumped into rather than out of them. They are cased through the material overlying the aquifer and if the earth materials are unconsolidated, a screen is placed in the well in the zone of injection (fig. 11). The purpose of the screen is to prevent the aquifer from caving into the bore hole and to permit access to the water-bearing materials. In some cases, several recharge wells may be installed in the same bore hole (fig. 12).

When compared to other techniques of artificial recharge, injection wells are generally both expensive to construct and to maintain. The major advantages lie in their ability to tap deep reservoirs and the fact that space requirements are small. Except in very permeable reservoirs their major disadvantage, other than cost, is their tendency to become plugged by the accumulation of fine-grained sediment in the aquifer adjacent to the well and to the buildup of slime brought about by the action of microbes. Thus, water quality is a major control factor in the use of wells for artificial recharge.

Injection wells are used for a variety of purposes other than for improving water supply. These include secondary recovery of petroleum, disposal of wastes and drainage. In a great many cases these procedures lead to ground-water contamination.

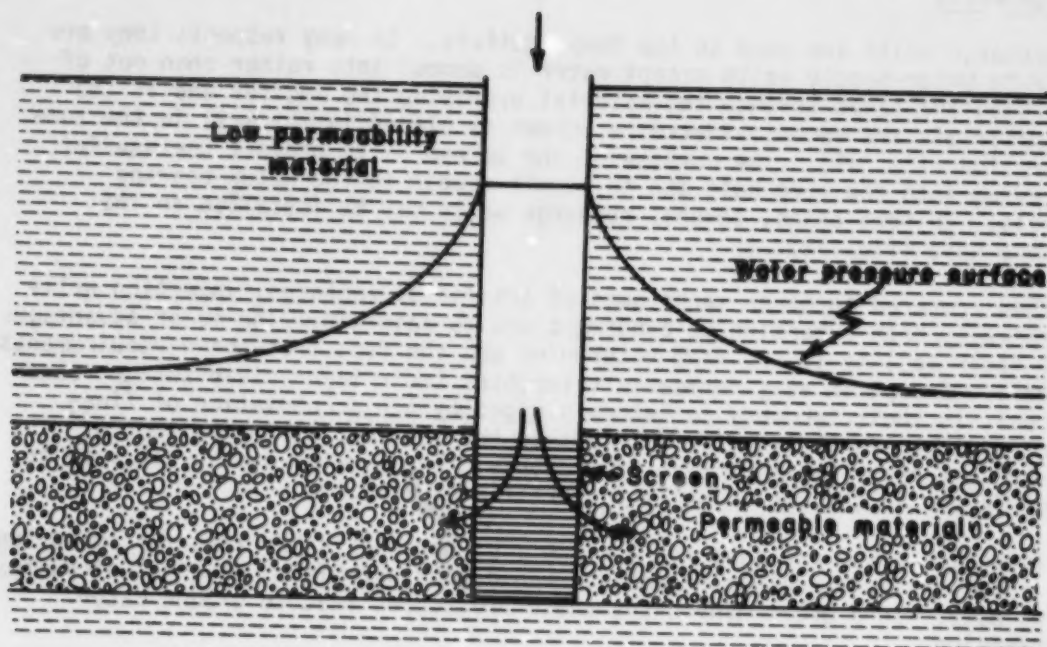


Figure 11. Recharge wells are commonly screened in the injection zone, which may be separated from the land surface by a considerable thickness of low permeability strata.

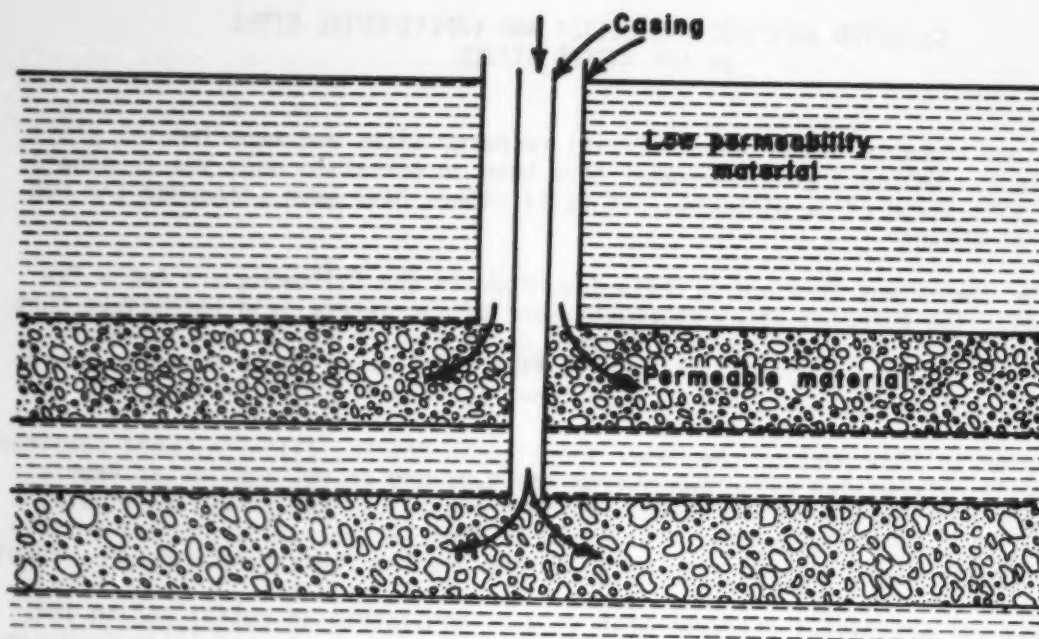


Figure 12. Some recharge wells consist of several lengths of pipe of different diameter installed one inside the other, which permits recharging several aquifer interbedded with confining layers.

SECTION 3

SELECTED RECHARGE FACILITIES AND EXPERIMENTAL SITES IN THE UNITED STATES

A considerable number of artificial recharge sites and experimental plots exist in the United States. Several have been in operation many years, others are in some stage of development, and still others have been abandoned for one reason or another.

The operations that are briefly described in the following are but a few examples. The selected cases represent some of the generalized techniques that have been developed over the past several decades. The key to any successful artificial recharge project is ingenuity--the development of an economical system that conforms to the geology, hydrology, and availability of property.

Prior to 1959 most of the water supplies in Peoria, Illinois, were obtained from wells. Excessive withdrawals from the sand and gravel aquifer at Peoria resulted in progressive water-level declines and by the early 1940's remedial measures were urgently needed. The Illinois State Water Survey decided artificial recharge might provide a solution to the problem (Suter and Harmeson, 1960).

Several artificial recharge methods were considered in detail and in 1949 a 10 m (30 ft) deep recharge pit was constructed adjacent to the Illinois River (fig. 13), where the ground-water level averaged 6 to 7.6 m (20 to 25 ft) below normal river elevation. Originally, a 15 cm (6 in.) layer of clean sand was placed in the pit to serve as a filter media. Because rapid plugging of the sand reduced infiltration rates, it was replaced with pea gravel. A second pit was constructed in 1956. Water flowed by gravity into the pits via a pipe from the Illinois River with the flow being manipulated in a control tower. The raw river water was chlorinated before it entered the pits.

The recharge rate when both pits were in operation was in excess of 17032 m³ (4.5 million gallons per day). The system resulted in an immediate and substantial rise in the ground-water level, particularly near the pits. The successful operation of the experimental recharge facility led to the construction of similar installations at industrial sites in Peoria.

For more than a half century, Minot, a town in northcentral North Dakota, has had occasional severe water problems ranging from periods of no stream flow to rapidly declining ground-water levels. Water rationing has often been involved. In 1916, the first well drilled into Minot aquifer showed there was considerable potential for ground-water development in the valley. Reportedly, the depth to water in 1916 was less than a meter (two feet) below land surface. Pumping caused the water level to decline about 4 m (12 ft) by 1929, 8.5 m (28 ft) by 1931, 14.6 m (48 ft) by 1939, and to 17.7 m (58 ft) by 1941.

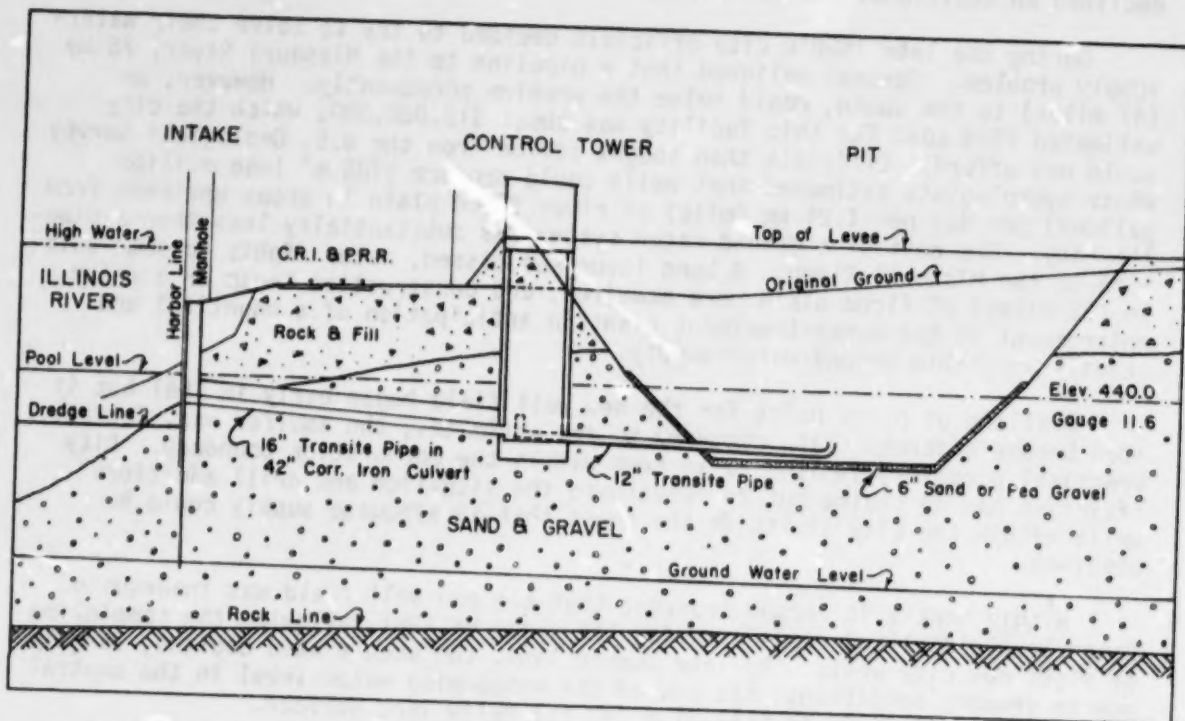


Figure 13. The experimental recharge pit at Peoria obtained its water supply from the Illinois River.

Mid-1952 began a wet period that lasted until late summer 1955. Discharge of the Souris River which bisects the city and provides part of its supply, increased substantially and the stream channel was scoured enough to permit a large amount of infiltration. The water level recovered about 5 m (17 ft), but the trend was again reversed during the next five years and the water level declined an additional 6 m (20 ft) by 1960.

During the late 1950's city officials decided to try to solve their water-supply problem. Several believed that a pipeline to the Missouri River, 76 km (47 miles) to the south, would solve the problem permanently. However, an estimated 1950 cost for this facility was about \$12,000,000, which the city could not afford. Officials then sought advice from the U.S. Geological Survey whose hydrologists estimated that wells could produce 3785 m³ (one million gallons) per day per 1.24 km (mile) of river flood plain in areas upstream from the city. The cost of a ground-water system was substantially less than a pipeline to the Missouri River. A bond issue was passed, water rights to some 35.5 km (22 miles) of flood plain were acquired, and construction began on a major enlargement of the water-treatment plant in anticipation of a bountiful and readily available ground-water supply.

Drilling of pilot holes for the new well field began early in 1961 but it soon became apparent that, contrary to the estimates, the aquifer was, for all practical purposes, limited to an area within the corporation boundary. City officials had no choice but to reevaluate the situation and drill additional wells within the city limits in the hopes that an adequate supply could be obtained.

Within months it became apparent that the new well field was inadequate. Water levels declined rapidly during the close of 1961 following the completion of eight new city wells. By late summer 1964, the accelerated decline, largely due to drought conditions, had caused the nonpumping water level in the central part of the well field to fall 21 m (70 ft) below land surface.

An investigation of the Minot aquifer, begun in the fall of 1963, showed that the annual daily pumpage from the aquifer exceeded the estimated rate of natural recharge and that it would be of little value to deepen existing wells or to drill new ones in the same aquifer (Pettyjohn, 1967).

Four solutions to Minot's water-supply problem were suggested:

1. Construct a dam on the Souris River flood plain to impound surface water;
2. Construct a pipeline to the Missouri River;
3. Develop a well field in a thick but unexplored, deep aquifer about 11 km (seven miles) down valley;
4. Artificially recharge the aquifer to halt or reduce the water-level decline.

The first three possibilities exceeded both the time and financial resources available to the city. Consequently, it was decided to examine

the feasibility of artificial recharge. In the fall of 1964, the potential for artificial recharge was investigated and by winter of 1965, construction of a recharge system was begun.

The recharge facility is contained within a pie-shaped 3 ha (7.5 acre) parcel of land. A recharge pit, constructed at the wide end of the site, fed into a Y-shaped canal system (fig. 14). Along the bottom of the canal were bored thirty-six .76 m (30 in.) diameter holes that were filled with gravel. Some months later, four large holes, about 4 m (12 ft) in diameter, were excavated and backfilled with gravel. The gravel-filled shafts permit water to infiltrate from the canals down through a layer of silt and clay into the aquifer (fig. 15). Water supply for the recharge system was obtained from the Souris River, approximately 305 m (1000 ft) south of the recharge site. The raw water was pumped directly from the river at a rate of about 15140 m³ per day (4 mgd), the maximum rate of recharge at the site (Pettyjohn, 1968).

A small dam on the Souris River was constructed several hundred meters downstream from the recharge site in order to deepen the water over the recharge pump intake, to augment the surface-water supply and to increase natural river infiltration in the vicinity of the well field. The entire recharge facility, including land purchase, engineering, and construction costs, amounted to approximately \$106,000. The cost of the dam was an additional \$87,000, and the total cost of the entire recharge system amounted to \$193,000. Annual maintenance and cleaning costs averaged about \$1,200. The cost involved in the construction of Minot's artificial-recharge facility were small in comparison to the benefits received, insignificant if compared with the cost of \$15,000,000 (1964) for a pipeline to the Missouri River, and infinitesimal if compared with the cost of a surface-water reservoir with a storage capacity equal to that of the Minot aquifer.

Several major benefits accrued from Minot's artificial recharge operation. Of prime importance was the rapid rise in water level throughout the entire aquifer. This rise, in places, exceeded 6 m (20 ft) after six months of operation. Future municipal withdrawals can be increased because of the large quantity of water added to underground storage. During optimum operating conditions at least 15140 m³ per day (4 mgd) were added to storage by artificial means and at least 11355 m³ per day (3 mgd) by natural infiltration from the surface and from underflow from adjoining ground-water sources. Much of this water previously flowed unused down the Souris River.

The greater part of the Dayton, Ohio, municipal water supply comes from wells on and near Rohrer's Island in the Mad River Valley in the northeastern part of the city. These wells yield an average of about 151,400 m³ per day (40 mgd); the peak pumpage is as high as 340,650 m³ per day (90 mgd). The supply is maintained by artificially recharging the aquifer, in what is probably the outstanding example of proper ground-water management in this part of the United States.

Infiltration ditches and lagoons covering a 8 ha (20 acre) area have been dredged and are flooded periodically to recharge the underlying aquifer. Flooding is accomplished by diverting water from the Mad River through a large intake pipe near the head of the island. Flow through this diversion is maintained

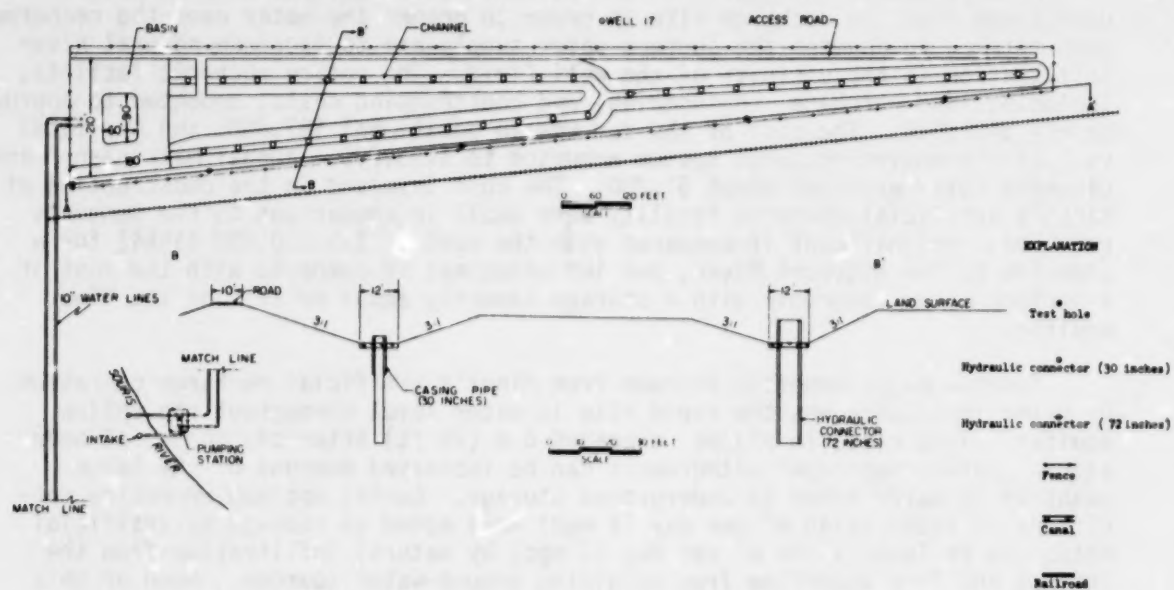
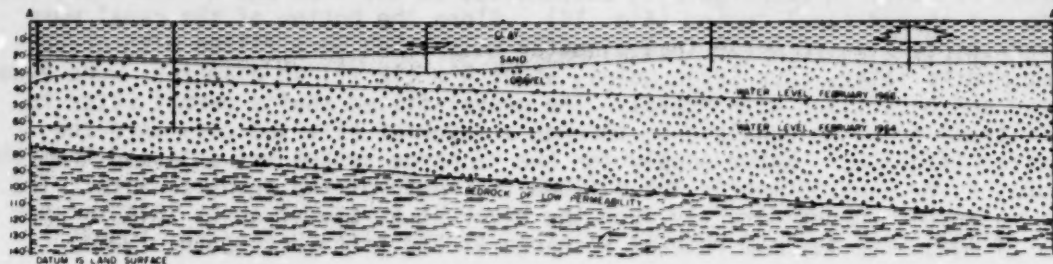


Figure 14. Geologic cross section and plan view of Minot's artificial recharge system.

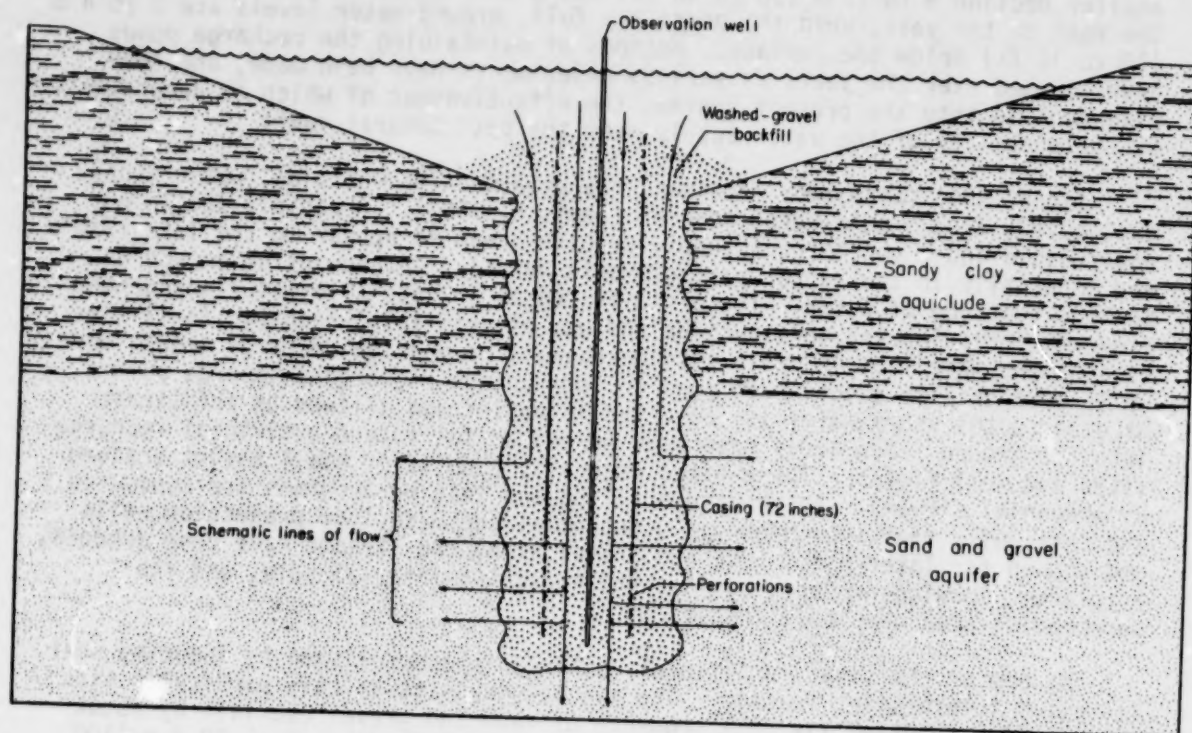


Figure 15. Hydraulic connectors at Minot are large diameter, gravel-filled shafts that penetrate a low permeability layer and permit direct access of the recharge water to the aquifer.

by a dam in the main channel of the river near the head of the island and by another dam about a kilometer below the intake pipe. The purpose of the dams is to raise the water sufficiently to cause flow into the infiltration areas. The lagoons and ditches are dredged each year to remove the bottom material and thus maintain a high rate of infiltration through the ponds.

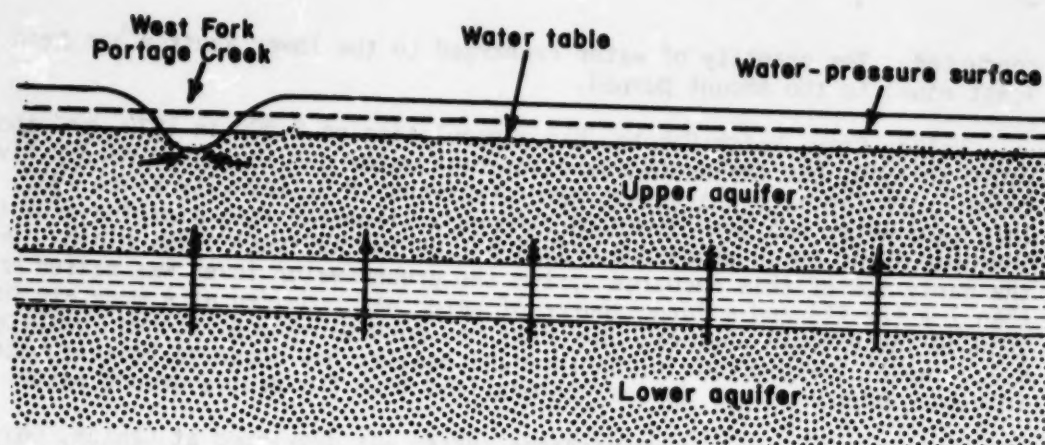
During the dredging operation when the ponds are dry, water levels in the aquifer decline 9 to 12 m (30 to 40 ft) below the land surface, but throughout the rest of the year, when the ponds are full, ground-water levels are 3 to 4 m (10 to 12 ft) below the surface. Methods of maintaining the recharge ponds have changed over the years as various experiments have been made, and they have evolved into the present system, the effectiveness of which is demonstrated by the stability of the water supply over the past several years.

Since 1869, Kalamazoo, Michigan, has obtained its municipal water supply exclusively from ground-water sources (Deutsch, 1967). A rapidly declining water table and a concomitant supply problem began to appear in the late 1930's and especially in the latter part of World War II. In view of an impending serious shortage of water, city officials began an intensive water-management program, including the construction and use of artificial-recharge facilities. Excavations were made in small stream channels to provide recharge ponds, and wells were drilled around each pond to form unique recharge-discharge points. At other sites storm water is collected in basins and allowed to infiltrate into the ground. New areas have been purchased for future artificial recharge sites and well fields. These sites generally consist of small basins drained by perennial streams. Systematic drilling and testing programs are conducted and test wells that show high yield potential are made into production wells and capped for later use. Sand and gravel along the streams have been dredged, in places, forming recharge basins, the excavated material sold, and the surrounding area developed into parks.

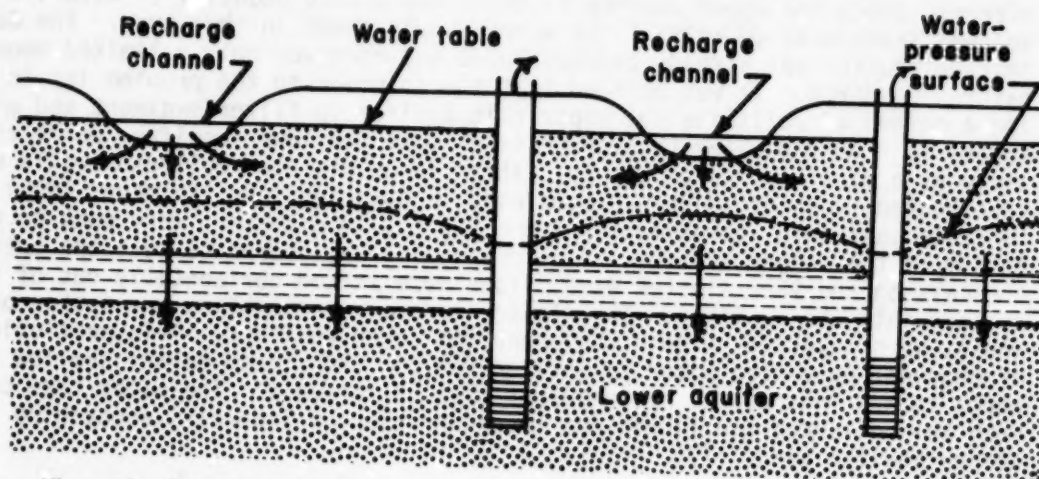
At one of the sites, artificial recharge is accomplished by inducing what is called interaquifer leakage. The glacial deposits at this particular site consist of a thick valley fill sequence of sand and gravel overlain by about 12 m (40 ft) of silt and clay, which in turn is covered by about 30.5 m (100 ft) of permeable sand. The surficial sand forms an aquifer that is in direct hydraulic connection with Portage Creek, a small stream that drains it.

Under natural conditions the water-pressure surface in the lower aquifer is higher than the water table in the upper sand, and leakage through the fine-grained material is upward (fig. 16). Pumping from the lower aquifer reversed the direction of leakage but sustained pumping would have resulted in objectionable declines in the deeper water-pressure surface with attendant increases in pumping lift and probable inflow of poor quality water from below.

An irregularly shaped recharge channel was constructed adjacent to Portage Creek. Water is diverted from the stream to the channel and maintained at a constant level. When water is pumped from the deep aquifer, surface water infiltrates from the recharge channel into the shallow aquifer, through the fine-grained material and into the deeper aquifer (fig. 16). After six years of pumping at the well field under recharge conditions water levels were essentially the same as they were at the time the original recharge tests were



Under natural conditions, water from the lower aquifer leaked upward through the confining bed to the shallow aquifer and eventually into Portage Creek.



When the lower aquifer was pumped, water migrated from the recharge channel to the upper aquifer and then through the confining layer to the lower aquifer permitting higher sustained well yields.

Figure 16. Diagrammatic sketch of the hydrogeological conditions at an artificial recharge site in Kalamazoo, Michigan.

conducted. The quantity of water recharged to the lower aquifer has been at least equal to the amount pumped.

Valley City, North Dakota, had a population of 5,000 in 1930, and about 8,000 in 1960, but during the same interval water use increased nearly five times. Artificial recharge has been practiced at Valley City since 1932. Since that time water has been diverted through a kilometer long pipeline from the Sheyenne River to an abandoned gravel pit on the adjacent flood plain. During the early use of this recharge system the ground-water level was raised more than 7 m (22 ft) and a large source of water was provided at a moderate price even during drought seasons. Not only has much water been stored for later use, gradual improvement in its chemical quality has occurred because water from the Sheyenne River is less mineralized than the native ground water.

An unusual ground-water recharge system was developed at Canton, Ohio, in the late 1940's. Trending through the northwestern part of the city is a buried glacial river valley, about a kilometer (3,000 ft) wide, that contains as much as 46 m (150 ft) of sand and gravel in the lower part. Overlying this aquifer is a layer of tight plastic clay that in turn is covered by 6 to 12 m (20 to 40 ft) of sand and gravel that forms a surficial aquifer. The West Branch of Nimishillen Creek crosses the buried valley and part of the flow in the stream is derived from water discharging from the shallow aquifer.

Water pumped from wells tapping the upper aquifer and adjacent to the stream would be replaced by induced infiltration as long as there was water in the stream. Since the upper aquifer is thin, the usable quantity of water in storage was inadequate to fulfill the water supply needs in that area. The deeper, thicker aquifer was already overdeveloped and received only a limited amount of natural recharge. It was decided that the solution to the problem lay in finding a method of utilizing the upper thin aquifer to filter sediment and micro-organisms from the water then connecting it to the lower aquifer, which could serve as a major source of supply. Three large diameter collector wells were constructed, each of which was completed in both aquifers (Kazmann, 1965). Concrete caissons, approximately 4.6 m (15 ft) in diameter, were sunk to the bottom of the deeper aquifer. A concrete plug was poured to seal the bottom of the caisson and then slotted steel pipes were jacked horizontally out of the caisson into the aquifers. The slotted laterals, resembling the spokes of a wheel, were injected in both the upper and lower aquifers. This particular arrangement permitted water to infiltrate from the stream to the shallow aquifer where it was intercepted by the upper tier of laterals. The water then cascaded down the collector and flowed out the lower tier of laterals, recharging the deeper aquifer (fig. 17).

The Canton recharge well was placed in operation in 1948 and permitted an average pumping rate from the deeper aquifer of approximately 22710 m³ per day (6 mgd). Between 1949 and 1961 there was no substantial change in the ground-water levels in the area.

At Fresno, California, investigations are being conducted involving the use of agricultural surface water for artificial recharge to augment an urban ground-water supply. This study, known as the Leaky Acres project, involves the use of 10 ponds into which are diverted irrigation waters, which infiltrate to the aquifer and become part of the ground-water supply.

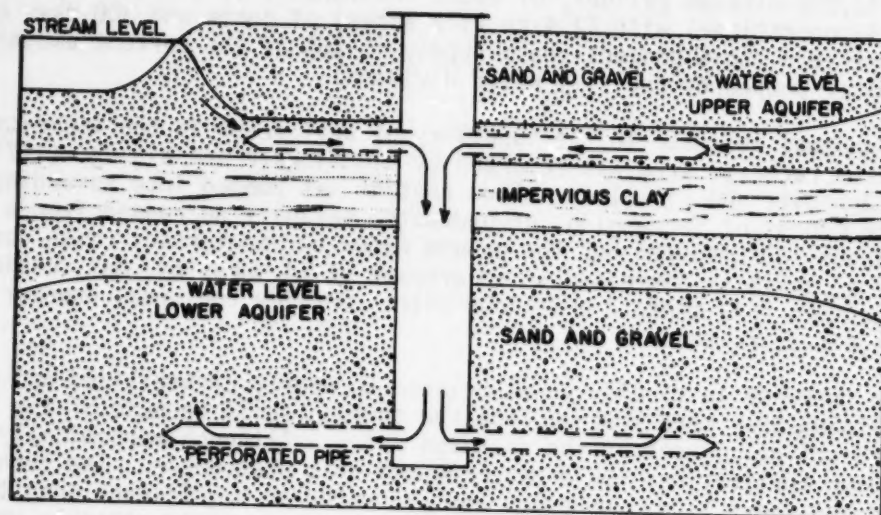


Figure 17. A large-diameter collector well at Canton, Ohio captures water from a stream and shallow aquifer and directs it through a series of laterals extending from the bottom of the caisson in order to recharge a deeper, heavily pumped aquifer.

The 10 basins forming Leaky Acres contain 47.4 ponded hectares (117 acres) for waterspreading. The recharge facility is situated on an alluvial fan. The fan deposits are very heterogeneous, both vertically and horizontally (Nightingale and Bianchi, 1973).

Prior to ground-water recharge the chemical quality beneath Leaky Acres had an average electrical conductivity of approximately 140 $\mu\text{mhos/cm}$. The water used for recharge, which is obtained from the Kings River via the Gould Canal, has a low mineral content. The conductivity of the canal water ranges from highs of 100-200 $\mu\text{mhos/cm}$ during the rainy season of December through February to lows of 30-40 $\mu\text{mhos/cm}$ during the summer when snowmelt is released from mountain reservoirs for irrigation. Recharge at Leaky Acres has noticeably decreased the ground-water salinity for a distance of about two kilometers in the direction of regional ground-water movement. During numerous recharge periods spanning the years from 1971 to 1975, more than 65.86 million cubic meters (17.388 billion gallons) of water infiltrated to the underlying aquifer. When fully operational with 47.4 ha (117 acres) of ponds and 300 days of recharge per year, this project could supply 15-25% of the current amount of ground water pumped by the city water division.

An unusual increase in the turbidity of well water in the vicinity of the Leaky Acres recharge area was reported by Nightingale and Bianchi (1977). Water of low turbidity and dissolved solids content was pumped into spreading basins. After six months of recharging, ground-water salinity decreased from a mean of 147 to about 100 $\mu\text{mhos/cm}$ but the ground water became turbid. With continued recharging, salinity decreased to an average of 74 $\mu\text{mhos/cm}$, but turbidity increased more than tenfold under the site. Outside the area, however, turbidity again decreased.

The increase in turbidity was related to poorly crystallized and extremely fine colloids that were leached from the surface soils because of the low dissolved solids content of the recharge water. Although economically unfeasible, gypsum applications would have reduced this phenomenon. The turbidity increase was short lived, however, and presented no significant long term problem. On the other hand, reactions such as these could possibly reduce the permeability of a recharge facility.

Salt water originating from San Francisco Bay in the vicinity of Palo Alto, California, is contaminating a near shore multiple aquifer system (Sheahan, 1977). A salt-water intrusion barrier is being constructed to reduce the potential of contamination of the ground-water supplies in this area. The salt-water intrusion barrier will consist of a series of injection wells that will recharge 7570 m^3 per day (2 mgd) of reclaimed wastewater into a shallow aquifer. The recharged wastewater will be removed by a similar series of extraction wells in order to avoid possible degradation of the aquifer and to allow reuse of the reclaimed water (fig. 18).

The three aquifers that occur within the area at depths of 6, 14 and 56 m (2, 45 and 185 ft) below land surface are separated by strata of low permeability. The injection/extraction wells are double cased and double screened, with neat cement grouting separating the two shallower aquifers. All three wells are installed in a 61 cm (24 in.) diameter drilled hole.

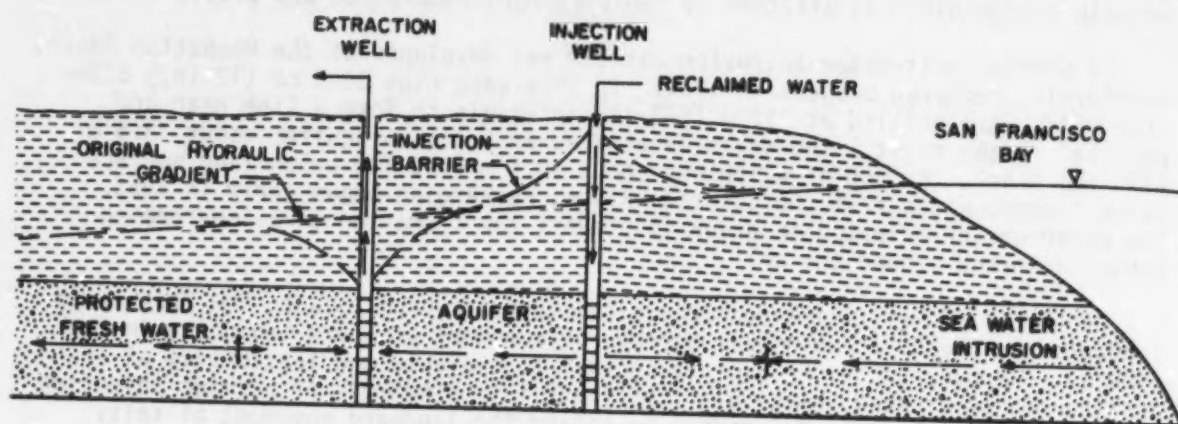


Figure 18. Diagrammatic illustration of operation of injection/extraction doublet (modified from Sheahan, 1977, p. 44).

In conjunction with the artificial recharge experiments at Palo Alto, other investigators are studying the transport and fate of organic compounds that occur in the injected wastewater (Rittmann and others, 1980). It is recognized that the use of reclaimed wastewater for direct recharge of aquifers provides the probability of introducing residual pollutants directly into the ground water. Questions concerning the fate and transport of organic substances in the subsurface are important in attempting to assess the risks that hazardous pollutants may provide to sources of water supply. Field studies, for example, indicate that some organic pollutants, such as naphthalene and heptaldehyde are biodegraded, while other compounds, such as chloroform and chlorobenzene are not. The latter, however, are affected to some extent by adsorption and the concentration of still others is reduced both by biodegradation and absorption. The movement of inorganic contaminants is affected by ion-exchange, adsorption and precipitation.

A similar salt-water intrusion barrier was developed at the Manhattan Beach, California, recharge project in 1951. In this case nine 30.5 cm (12 in.) diameter wells were drilled at 152 m (500 ft) intervals to form a line near and parallel to the coast. The wells penetrated an artesian aquifer about 33.5 m (110 ft) thick, the top of which was about 30.5 m (100 ft) below land surface. Using treated water from the Colorado River, recharging began early in 1953. The water was chlorinated in order to prevent the formation of slime-forming bacteria in and around the well.

A series of artificial recharge experiments on Long Island, New York, were conducted by the U.S. Geological Survey for a number of years beginning in the 1960's. The purpose of the experiments was to evaluate the feasibility of injecting highly treated sewage plant effluent into a network of barrier injection wells with the intention to prevent or retard the landward movement of salty water from the Atlantic Ocean into major aquifers beneath Long Island (Cohen and Durfor, 1967). The experimental injection well, which is about 152 m (500 ft) deep, consists of two adjacent fiberglass casings with stainless steel screens that tap the Magothy aquifer.

The aquifer was recharged with tertiary treated sewage during a research phase between 1968 and 1973. The reclaimed water was injected into very fine to medium sand, which contained some silt and clay. Clay in the aquifer consists of equal parts of kaolinite and illite. Particles and layers of lignite are also present, as are pyrite and marcasite. Dissolved solids content of the native water in the Magothy ranged between 22 and 25 mg/l, while that of the reclaimed water had a mean concentration of 398 mg/l (Ragone and Vecchioli, 1975).

During recharge a number of reactions occurred within the aquifer that resulted in a degradation in water quality with respect to iron concentrations and pH. Iron concentrations in the water increased from a 0.14 to 0.30 mg/l range to as much as 3 mg/l (recommended limit is .3 mg/l) as reclaimed water replaced native water. Presumably the increase was due to the dissolution of pyrite and marcasite. The pH of the water decreased from a native 5.22 to 5.72 range to a low of about 4.50. Iron concentrations increased and the pH decreased with increasing distances from the recharge well. A common problem with this recharge system was the continual clogging of the screen with bacterial slime and sediment.

The U.S. Marine Corps base at Camp Pendleton has been operating an extensive water program since 1943 (Schmidt and Clements, 1977). The water supply for the base is obtained from four deep ground-water basins. The basins are continuously recharged with reclaimed effluent, surface runoff, and precipitation. Recharge in the Santa Margarita River basin is accomplished by on-channel water spreading structures, off-channel water spreading structures, recycling of sewage effluent, phreatophyte control, and erosion reduction structures (fig. 19). During the rainy season water from the Santa Margarita River is diverted either into Lake O'Neill or to off-channel spreading basins that have very high infiltration rates. The lake serves as a storage reservoir. Nine on-channel water spreading structures lie on the riverbed below Lake O'Neill. The waters spread out forming shallow lakes behind a series of low levees that cross the channel. Effluent from five sewage treatment plants is used to recharge the basins and to maintain a salt-water intrusion barrier. The total cost for the recharge operation in 1972 amounted to \$15 per 3785 m² (million gallons).

The Hemet-San Jacinto ground-water basin is an important source of irrigation and drinking water for the local area (Schmidt and Clements, 1977). In July, 1965, the Eastern Municipal Water District completed the construction of a new sewage treatment plant. Shortly thereafter the U.S. Environmental Protection Agency provided funds for a project to demonstrate the feasibility of recharging the ground-water basins with treated secondary effluent. Since that time, treated wastewater has been spread in recharge basins, both as a method of disposal and for replenishing the ground water.

The recharge area consists of 10 ponds covering an area of approximately 6.5 ha (16 acres). The ponds are arranged in two parallel groups and the reclaimed water can be diverted into any combination of ponds. The basins are interconnected with overflow gates to allow transfer of water from one basin to another. Each basin requires about one day to fill and two days to drain. The pond is then permitted to dry for at least one day in order to reduce algal growths, which reduce the rate of infiltration. The basins are periodically rototilled. In 1972 the total cost for the recharge system, including equipment amortization and overhead, amounted to \$22,100 per year for an average flow of 7570 m³ per day (2 mgd), or approximately \$30 per 3785 m² (million gallons).

In 1967, an experimental high rate land application system, called the Flushing Meadows project, was installed in the bed of the Salt River west of Phoenix, Arizona (Schmidt and Clements, 1977). The purpose of the project was to study the feasibility of renovating secondary effluent from unrestricted irrigation, recreation, and certain industrial uses. The recharge system consists of six basins 6 m (20 ft) wide and 213 m (700 ft) long spaced 6 m (20 ft) apart (fig. 20). Secondary effluent is pumped from a channel into the basins. Gravel dams were placed across the basins, about 15 m (50 ft) from the inlets, to form sedimentation basins. Because of the successful experiments at Flushing Meadows, the City of Phoenix has completed construction of a 56775 m³ per day (15 mgd) wastewater recharge/extraction facility. The project is a first step toward extensive wastewater renovation and reuse.

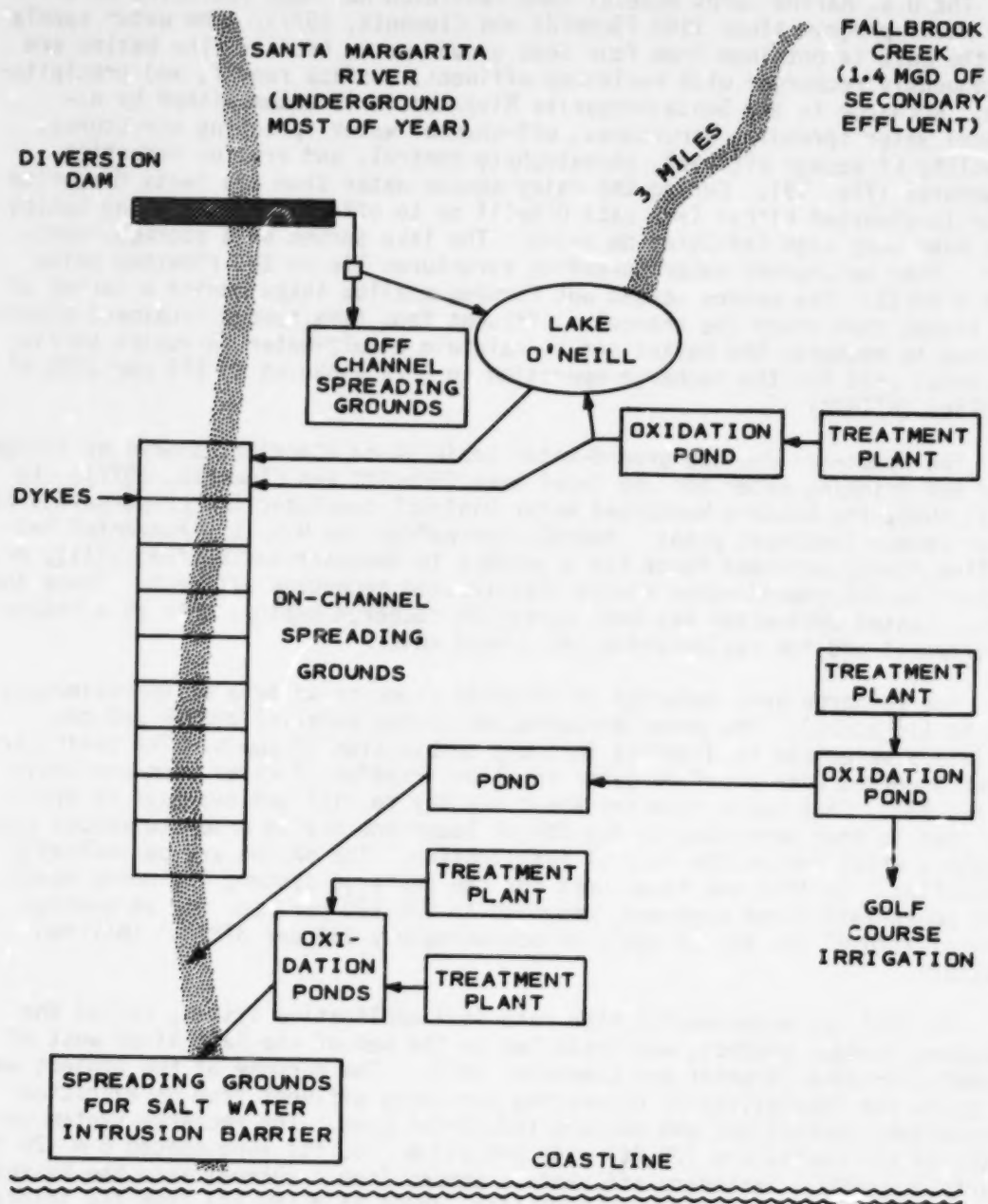


Figure 19. Schematic of the ground-water recharge system at Camp Pendleton, California.

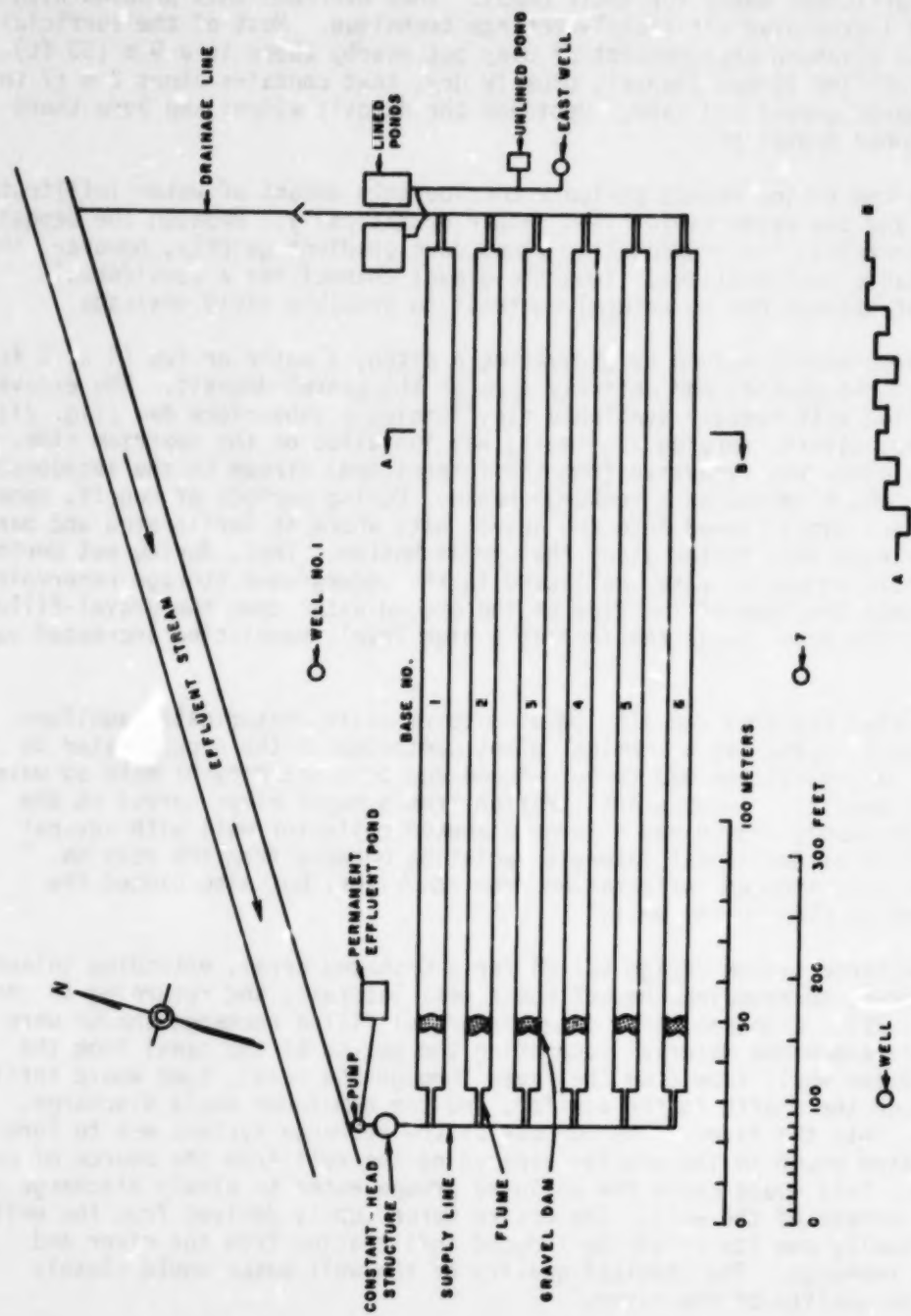


Figure 20. Plan view of the Flushing Meadows artificial recharge facility at Phoenix, Arizona.

The village of Glenburn in north-central North Dakota had a difficult time supplying sufficient water for their needs. They overcame this problem with an unusual and inexpensive artificial-recharge technique. Most of the surficial rocks in the Glenburn area consist of clay but nearby there is a 9 m (30 ft) wide gravel-filled stream channel, usually dry, that contains about 2 m (7 to 8 ft) of coarse gravel and sand. Upstream the deposit widens and here there is an abandoned gravel pit.

During the spring runoff period a considerable amount of water infiltrates the gravel and the water table rises rather dramatically. Because the deposits are very permeable, the ground water flows down gradient quickly, however, and the water table soon declines. Thus the gravel channel has a considerable capacity for storage but no natural controls to prohibit rapid drainage.

This problem was solved by excavating a ditch, a meter or two (4 or 5 ft) wide, across the channel and entirely through the gravel deposit. The excavation was backfilled with readily available clay forming a subsurface dam (fig. 21). A perforated culvert, serving as a well, was installed on the upstream side. A diversion ditch was excavated from the intermittent stream to the abandoned gravel pit, which served as a recharge basin. During periods of runoff, some of the surface water flowed into the gravel pit, where it infiltrated and part of the remainder infiltrated along the stream bottom. Thus, during wet periods a considerable amount of water collected in the underground storage reservoir. The subsurface dam impeded the flow of the ground water down the gravel-filled channel and the water table remained at a high level, permitting increased water usage.

Artificial recharge can also be used to renovate contaminated aquifers. Waste disposal lagoons at a chemical plant contaminated the ground water so seriously that operations had to be reduced due to a scarcity of make up water of adequate quality. Induced infiltration from a major river served as the supply. The supply source was a large diameter collector well with several hundred meters of horizontal laterals radiating outward from the cession. Pumping not only induced infiltration from the river, but also caused the contaminants to flow to the well.

The recharge system design called for a U-shaped canal, extending inland from the river, surrounding the collector well laterals, and returning to the river (fig. 22). Eighteen large diameter gravel filled recharge shafts were to penetrate fine-grained material separating the bottom of the canal from the aquifer. Water would flow from the river through the canal, some would infiltrate through the shafts to the aquifer, and the remainder would discharge, downstream, into the river. The purpose of the recharge systems was to form a ground-water mound in the aquifer separating the well from the source of contamination. This would cause the polluted ground water to slowly discharge into the river instead of the well. The entire water supply derived from the well would eventually owe its origin to induced infiltration from the river and artificial recharge. The chemical quality of the well water would closely resemble the quality of the river.

Water supply problems in arid regions are particularly vexing because of scanty rainfall and the high rate of evaporation. In some situations, it may

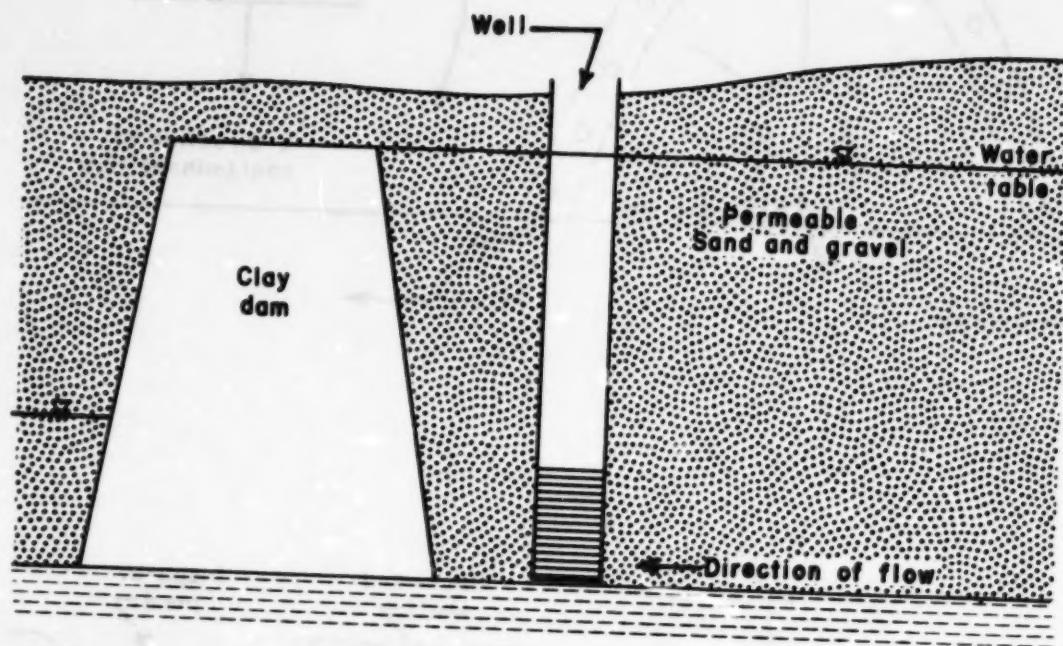


Figure 21. A subsurface dam of clay impeded the flow of ground water in a pond and gravel-filled channel in the vicinity of Glenburn, North Dakota.

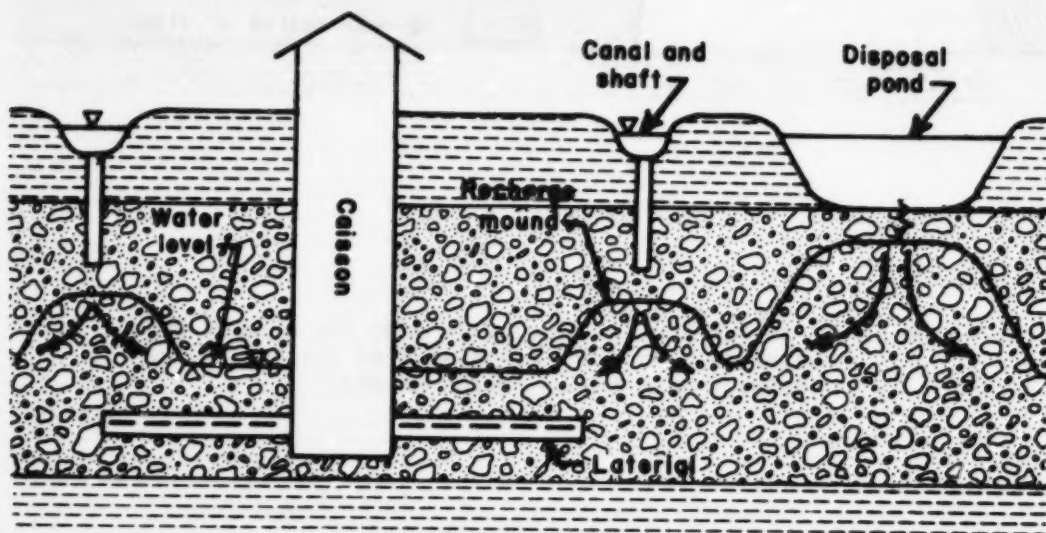
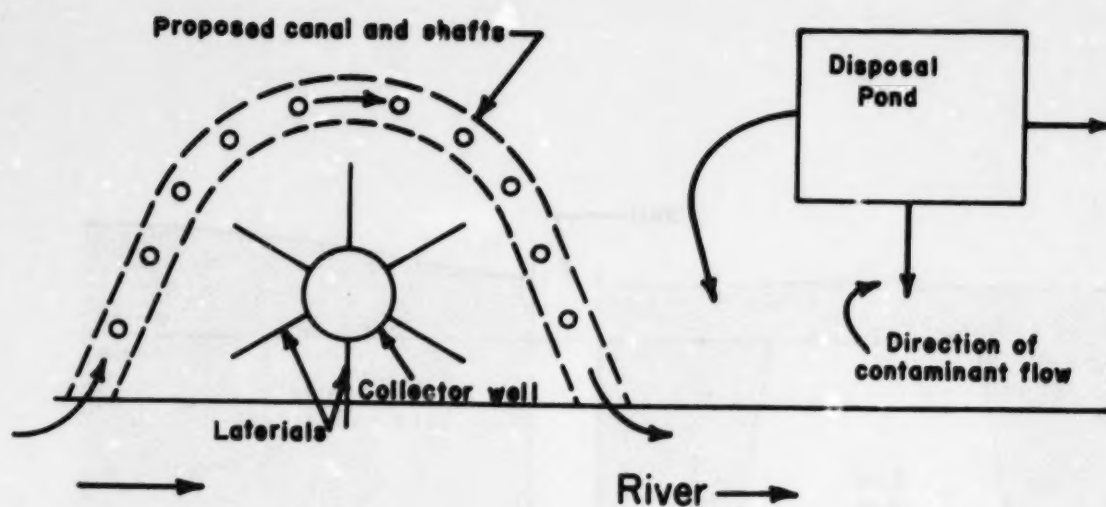


Figure 22. Proposed artificial recharge system to improve ground-water quality at an industrial complex.

be possible to augment supplies not only by artificial recharge but also by constructing artificial aquifers. Artificial aquifers, by necessity, can store only moderate quantities of water, but they are labor intensive and, therefore, can be built at a modest equipment cost.

The design and construction of an artificial aquifer at the Santa Clara Indian Reservation, New Mexico, was described by Helweg and Smith (1978). A small gulley, several meters wide, was cleared of vegetation, deepened, and sloped. Spoil material was used to construct an earthen dam across the gulley. A trench was cut adjacent to and parallel with the dam into which was installed slotted plastic pipe. The slotted pipe was connected, at a right angle, to a second pipe, extending through the dam in the low point of the gulley. The second or discharge pipe was laid on a slight downslope grade (fig. 23) and installed prior to dam construction.

Once the gulley was shaped, the pipes installed and the dam built, plastic lining was placed on the floor of the structure. The gulley was then backfilled with uniform sand (gravel could be used) and topped off with gravel mulch, thus completing the artificial aquifer.

During the rainy season or periods of surface runoff, water flowed down the gulley and infiltrated through the gravel mulch to the artificial aquifer. In some cases, it might be necessary to construct a spillway to avoid excessive erosion of the dam. Water is removed from the reservoir via the discharge pipe, the rate being controlled by a valve.

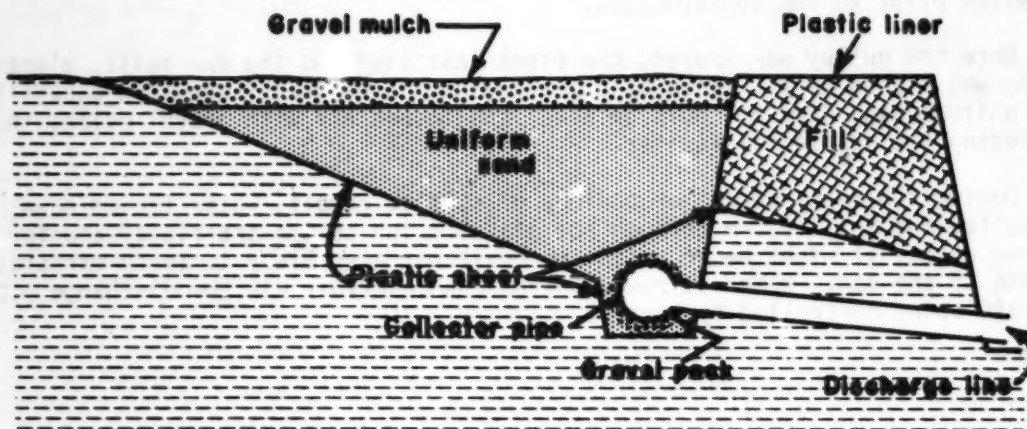


Figure 23. Schematic of an artificial aquifer.

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